Title: Meta-awareness, mind-wandering, and the control of 'default' external and internal orientations of attention

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Abstract

The "default mode" of cognition usually refers to an automatic tendency to simulate past, future, and hypothetical experiences, rather than attending to external events in the moment. "Mind-wandering" usually refers to moments when attention drifts from external tasks to become engaged in internal, default-mode cognition. Both definitions are perhaps limited: the mind can be caught by external objects when attending internally, and objects in the external world can be just as captivating as internal thought, causing attention to drift. To explore the relationship between prepotent internal and external default modes and the bi-directionality of mind-wandering, we measured brain activity in forty participants using fMRI during performance of a focused attention task. Naturalistic movie clips were presented four times in sequence. When subjects tried to focus attention on the videos, more mind-wandering events (distractions from the externally-focused task) occurred as the videos became less interesting with each repetition, and when less engaging videos were presented. When subjects focused internally on their own breath, more mind-wandering events (distractions from the internally-focused task) occurred when videos were most interesting (i.e. on the first repetition) and when more engaging videos were presented. In the whole-brain fMRI data and also in focused analyses of sensory areas and default mode areas, inter-subject correlation analysis revealed cortical signals of attention that corroborated the behavioral results. We suggest that whether the default state is internal or external, and whether the sources that disrupt it are internal or external, depend on context.

Significance Statement

The "default mode" of cognition usually refers to an automatic tendency to simulate past, future, and hypothetical experiences, rather than attending to external events in the moment. "Mind-wandering" usually refers to moments when attention drifts from external tasks to become engaged in internal, default-mode cognition. We used a focused attention task and whole brain synchrony to study involuntary shifts of attention bi-directionally, between external and internal default states. We found that mind-wandering can occur bi-directionally and whether an internal focus or an external focus should be considered a default state depends on context.

Introduction

We are captured by the objects of our attention. Such objects can be external (e.g. a cute cat) or internal (e.g. a fond memory). Some researchers have suggested that we are more frequently drawn to internal objects than we are to external sensory perceptions (1). This 'internal bias' of attention is a result of the stable and predictable environment humans commonly find themselves in. Because we often engage in habitual routines (e.g. the same commute to work each day), it is more valuable to think about previous experiences and to plan for upcoming scenarios than it is to pay attention to predictable external events. As a result, the landscape of human thought is automatically tuned towards internal thoughts and periodically the strength of this internal pull is so strong that we may miss important cues in the environment, such as a sign on the highway.

Decades of neuroimaging have found one network to be associated with this kind of internal thought, named the Default Mode Network (DMN) (2, 3). The default mode – the simulation of past, future and hypothetical experiences – is the common orientation of attention in the absence of an explicit task goal. This network is associated with a variety of internal processes, including mind-wandering (4), spontaneous cognition (5), creativity (6), and goal directed memory retrieval (7). In contrast, this network deactivates, while other regions come online, when the focus of attention turns towards external events and stimuli (8). While some have recently challenged the view that the DMN is primarily involved in internally oriented cognition (9), it is considered established in the literature that there is a distinction between external and internal attention (10) and that there is a neural basis for a default, internally oriented mode of cognition (11).

The standard view of a default internal orientation, however, hides some complexity. It could be argued that "default" applies equally well to internal and to external modes, depending on circumstances. The brain naturally moves to one state or the other depending on which environment is more interesting. For example, when external stimuli have more attentional pull, then external attention becomes the default, and it takes extra cognitive effort to pull attention internally. Contexts in which external content can be just as captivating as internal thought are increasingly prevalent in the modern world: recent evidence shows that 25% of adults and 45% of US teens engage with social media 'almost constantly' (12) and often face challenges disengaging from these sources (13). Many have ventured that such uncontrolled engagement warrants classification as a mental health disorder, as uncontrolled use has been shown to produce detrimental effects on personal, social, and professional life (14, 15) as well as on cognition (16). Thus, internal and external sources can provoke similar uncontrolled modes of attention.

Mind-wandering is usually studied in tasks where people try to attend externally but wander to internally oriented cognition (17). In contrast, the study of meditation measures the ability of individuals to maintain attention on a single internal task while resisting the attraction of free, unconstrained thinking. In the meditation literature, therefore, mind-wandering is usually considered a transition from on-task internal content to off-task internal content (18). Neither perspective typically considers the case when attention is supposed to be maintained on an internal task but is distracted by external events and control is required to resist the external distraction. Thus, "mind-wandering" as a term could just as fruitfully be applied to internally or externally oriented cognition. In some cases, the mind involuntarily drifts from desired external to distracting internal cognition, as is traditionally studied in mind-wandering. But in other cases, people may try to attend internally and become distracted by external events. The mind-wandering processes may be quite similar in both cases, or involve evolution of attention states according to similar principles.

Controlling one's own attention to prevent mind-wandering involves at least two cognitive functions: first, becoming aware of the current state of attention, and second, directing attention based on that assessment (19). The first function is often referred to as meta-awareness, or the explicit knowledge of the contents of thought (20). Meta-awareness is believed to reduce the frequency of mind-wandering (21). Meta-awareness naturally occurs intermittently in dynamic thought, but can be primed to occur more frequently if the task requires it. In the study of mind-wandering, sometimes people are asked to continuously monitor their attentional state for lapses, a method often denoted as 'self caught' (22). Another method is to give people intermittent reminders to use meta-awareness to check their attentional state (23).

In the present study, we asked two questions. First, can we find behavioral evidence that people do indeed switch attention between internal and external targets, and that the default, or "prepotent" state of attention switches from external to internal depending on circumstance? Second, can we find neural evidence from functional magnetic resonance imaging (fMRI) data that corroborates these dynamic shifts of attention between external and internal states?

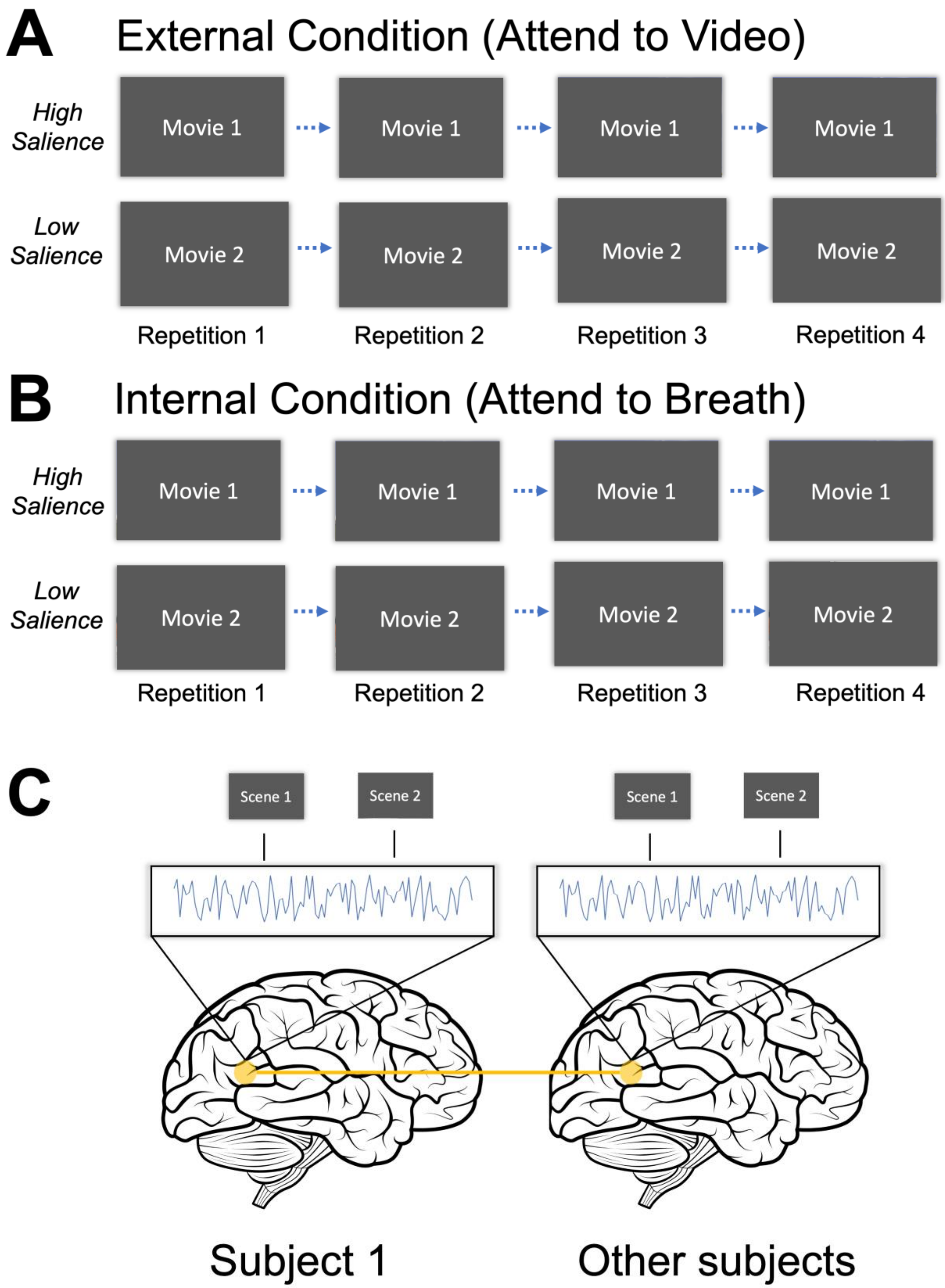
A
External Condition (Attend to Video)
High Salience
Movie 1
Movie 1
Movie 1
Movie 1
Low Salience
Movie 2
Movie 2
Movie 2
Movie 2
Repetition 1
Repetition 2
Repetition 3
Repetition 4
B
Internal Condition (Attend to Breath)
High Salience
Movie 1
Movie 1
Movie 1
Movie 1
Low Salience
Movie 2
Movie 2
Movie 2
Movie 2
Repetition 1
Repetition 2
Repetition 3
Repetition 4
C
Scene 1
Scene 2
Scene 1
Scene 2
Subject 1
Other subjects

Figure 1. Experimental paradigm. Participants viewed a total of six videos during the experiment. Videos were categorized as high or low salience. Participants switched attention condition following three movies. **A.** In the external attention condition, a ~2 minute video clip was presented on screen. Participants were instructed to pay attention to the video and press a button if they noticed that their mind had wandered from the video content. Participants repeated each task four times in a row, sequentially viewing the same video and indicating any lapses of attention. **B.** In the internal attention condition, participants viewed another ~2 minute video clip, this time tasked with ignoring the external video and instead focusing on their breathing. Participants repeated each task four times in a row, sequentially viewing the same video and indicating any lapses of attention. **C.** Inter-subject correlation (ISC) was used to identify voxels that processed external information similarly across all subjects. To calculate ISC, the activation pattern of all voxels during stimulus presentation was extracted for one subject and correlated to the average timeseries across all other subjects for each respective voxel. This procedure was rotated for each subject. Subjects' whole-brain ISC maps were averaged together to generate a final ISC image corresponding to voxels that exhibited similar time courses of activation across participants.

We presented participants with 2-minute clips from movies. In one condition, the external attention condition, we asked participants to attend to the movie and to press the button when they noticed that their attention had wandered off the movie (i.e., to self-report mind-wandering events; Figure 1A). In a second condition, the internal attention condition, we asked them to ignore the movie, attend to their own breathing, and press the button when they noticed their attention wandering off of their breathing (Figure 1B). In both attention conditions, subjects watched four repetitions of the movie, back to back. We expected the movie to become harder to attend with each repetition. We also tested six different movies, three categorized as "high salience" and three as "low salience." In this way we varied the salience and interest value of the external stimuli to study the effect on attention and mind-wandering.

We hypothesized that in the external attention condition, maintaining attention on task would become more difficult with each repetition of the movie, and would also be more difficult for the low salience movies. This reduction of attention should be accompanied by more mind-wandering and thus a higher frequency of button presses. In contrast, in the internal attention condition, when subjects needed to ignore the movie and focus on their breath, attention to the task should become easier with each repetition of the movie and should also be easier for low salience movies. This improvement in on-task focus of attention should be accompanied by a lower frequency of button presses. In this way, we should be able to track the dynamics of an external task with mind-wandering, and an internal task with external distractors inducing mind-wandering.

We further hypothesized that the effects of meta-awareness and control of attention would be measurable in cortical fMRI signals. The representation of the external video stimulus should be stronger and more widespread in the brain when the task is to pay attention externally, when the video is presented for the first time, and when the type of video is high salience. In contrast, the representation of the external video stimulus should be disrupted when the task is to pay attention internally, when the video has already been seen and is now being repeated, and when the type of video is low salience. Of particular interest to this analysis, we examined regions of interest (ROIs) in brain areas associated with low-level sensory processing, including visual and auditory areas, and ROIs associated with high-level cognitive control, including brain areas in the DMN.

Methods

Subjects

Forty healthy human volunteers (aged 18-21, normal or corrected to normal vision, 37 right handed, 17 female) were recruited from the community and from a subject pool sponsored by Princeton University. All subjects provided consent and received course credit for participation or monetary compensation. One subject was excluded due to scanner malfunction. All procedures were approved by the Princeton Institutional Review Board.

Experimental Setup

Subjects lay supine on the MRI bed. Visual stimuli and video content were displayed using PsychoPy2 (24) and projected onto a screen 80 cm from the eyes through an angled mirror mounted on top of the head coil using a digital light processing projector (Hyperion MRI Digital Projection System, Psychology Software Tools, Sharpsburg, PA, USA) with a resolution of 1920 x 1080 pixels at 60 Hz. Audio for each video was delivered with MRI-compatible Sensimetrics in-ear headphones. All responses were recorded using a button box held in the subject's right hand and operated with the index finger.

Movie Stimuli

Six movie stimuli were used. Three originated from widely popular mainstream media sources, including a clip from BBC's TV drama series Sherlock (2 m 19 s), Dreamwork's animated comedy Shrek (2 m 7 s), and NBC's sitcom the Office (2 m 25 s). In Shrek, the ~2 minute clip consisted of a personal discussion between two characters about one character's feeling of prejudice; in Sherlock, the scene comprised an initial synopsis of a crime scene; in the Office, three characters interacted comically in a skit. These movies were selected on the basis of their popularity and engaging story lines encompassing vulnerability, drama, and comedy, respectively. Our hope was that these videos would be highly engaging to participants, and for this reason we categorized them as 'high salience' videos. In contrast, the second set of three videos were instructional videos selected from YouTube: How to Make an Origami Heart (1 m

55 s), How to Bake a Cake (2 m 21 s), and How to Brush your Teeth (2 m 9 s). Our hope was that instructional videos on simple tasks would elicit less engagement compared to video content professionally designed to captivate audiences. We therefore categorized them as "low salience" videos. To measure the efficacy of high versus low salience categorization, at the end of the experiment participants were asked to rate how engaging each movie was on a scale from 1 to 10.

Task Design

The task design is shown in Figure 1. All subjects participated in two attention conditions. In the external attention condition, a video clip was presented on screen. Participants were instructed to pay attention to the video and press the button if they noticed that their mind had wandered from the video content. Mind-wandering was explicitly defined as content on mind that was unrelated to the content of the video, such as thinking about potential dinner plans or memories about the previous weekend. Participants repeated this task four times in a row, sequentially viewing the same video and indicating any lapses of attention to the video with button presses. Once they finished four repetitions, participants were given an optional 30 s of rest and an opportunity to communicate with the experimenter. In the second condition, the internal attention condition, participants viewed another video clip (different from the video seen during the external attention condition), and this time were tasked with ignoring the video and instead focusing on the rhythmic sensation of their breathing, silently reciting "breathe in, breathe out" while keeping their eyes open and on screen. Once again subjects were instructed to press the button if they noticed that their mind had wandered from their breathing, for example if their mind had wandered to the content of the video. The internal attention task was completed four times, with the same video presented each time. Thus one complete run of the external attention condition consisted of focusing on a video for four repetitions, and one complete run of the internal condition consisted of focusing on breath and ignoring an external video for four repetitions.

Participants completed three runs of the external attention condition and three runs of the internal attention condition. For each run, a unique video clip was used. All participants viewed the same six videos, but the attention condition (external, internal) and order of movie presentation were randomized for each subject. The six videos were pseudo-randomly sorted into two groups, with two high salience videos and one low salience video assigned to group A, and one high salience and two low salience videos assigned to group B. Half of participants completed the external condition using the three videos in group A and the internal condition using the three videos in group B. The other half of participants did the opposite, completing the internal condition using the three videos in group A and completing the external condition using the three videos in group B. Within each set of three videos, the order of videos was randomly varied between subjects. Finally, half of participants began the experiment performing three runs of the external attention condition followed by three runs of the internal condition, and the other half began with the internal attention condition followed by the external condition.

fMRI Data Acquisition

Functional imaging data were collected using a 3T MAGNETOM Skyra scanner (Siemens Healthineers AG, Erlangen, Germany), equipped with a 64-channel head/neck coil. Gradient-echo T2*-weighted echo-planar images (EPI) with blood oxygen level dependent (BOLD) contrast were used as an index of brain activity (25). Functional image volumes were composed of 40 near-axial slices with no interslice gap and an in-plane acceleration factor of 2 using Generalized Autocalibrating Partially Parallel Acquisition (GRAPPA), with slice thickness = 3.0 mm, field of view (FOV) = 200 mm, 80 x 80 matrix, 2.5 mm x 2.5 mm in-plane resolution, echo time (TE) = 30 ms, flip angle = 70°, and bandwidth of 1690 Hz/Px.

Before functional runs, matching spin-echo EPI pairs with reversed phase-encode blips produced pairs of images with distortions going in opposite directions for blip-up/blip-down susceptibility distortion correction. An additional high-resolution structural image was collected for each participant, with 3D magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequence, voxel size = 1 mm isotropic, FOV = 256 mm, matrix size = 256 x 256, 176 slices, TR = 2300 ms, TE = 2.96 ms, inversion time (TI) = 1000 ms, flip angle = 9°, iPAT GRAPPA = 2, bandwidth = 240 Hz/Px, anterior-posterior phase encoding, and ascending acquisition.

fMRI Preprocessing

Data were preprocessed using FMRIPREP version 1.2.3 (26). T1-weighted volumes were corrected for intensity nonuniformity using N4BiasFieldCorrection v2.1.0 (27) and skull-stripped using the OASIS template in antsBrainExtraction.sh v2.1.0. Spatial normalization through nonlinear registration to the ICBM 152 Nonlinear Asymmetrical template version 2009c (https://nist.mni.mcgill.ca/icbm-152-nonlinear-atlases-2009/) was completed using the antsRegistration tool of ANTs v2.1.0 (28). Brain tissue segmentation of cerebrospinal fluid (CSF), white-matter (WM) and gray-matter (GM) using Fast (29) was performed on extracted T1w images.

Functional data were slice time corrected using 3dTshift from AFNI v16.2.07 (30) and motion corrected using mcflirt (FSL v5.0.9) (31). Flirt (FSL) performed boundary-based registration with six degrees of freedom to co-register the corresponding T1w images to functional data (32). Motion correcting transformations, BOLD-to-T1w transformation, and T1w-to-template Montreal Neurological Institute (MNI) warp were concatenated and applied in a single step using antsApplyTransforms (ANTs v2.1.0) using Lanczos interpolation. All functional images were high-passed (0.007) using Nilearn's signal cleaning function (https://nilearn.github.io/stable/modules/generated/nilearn.signal.clean.html). For further description of fMRIprep's preprocessing pipeline see: https://fmriprep.readthedocs.io/en/latest/workflows.html.

In additional preprocessing procedures, confound regression was performed to minimize the effects of physiological noise, head motion and scanner drift. Physiological noise regressors were determined through aCompCor using the CSF and WM masks projected from subject-specific space to the T1w space. The first 5 principle components for CSF and WM were selected for each functional run, totaling 10 aCompCor components. Head motion parameters included 3 translation and 3 rotation time series as well as censor time series for volumes with a framewise displacement (FD) exceeding 0.5 mm. Before each movie repetition, a 7.5 second countdown was displayed on screen. This data was trimmed so that only TRs consisting of the movie presentation were used for analysis. Three buffer TRs were appended to the end of each repetition to account for hemodynamic lag.

fMRI Analysis: Inter-Subject Correlation

In conditions when participants attend to the external movie stimulus, the stimulus should influence their brain activity in a manner that is temporally correlated among the participants. In contrast, in conditions when participants are paying little or no attention to the movie stimulus, the stimulus should evoke less temporally correlated brain activity among subjects. Instead, cognitive processes unique to each subject will prevail and result in uncorrelated activity. As illustrated in Figure 1C, inter-subject correlation (ISC) was used to identify voxels that processed external information similarly across all subjects (33, 34). To derive this measure, we used Brainiak's Leave One Subject Out ISC function (35). To calculate ISC, the activation pattern of all voxels during stimulus presentation was extracted for one subject and correlated to the average timeseries across all other subjects for each respective voxel. This procedure was rotated for each subject, iteratively calculating the correlation of one subject's activation patterns to the group's activation patterns. This analysis produced an ISC value for every held-out subject at every voxel. We then averaged the held-out subjects' whole-brain ISC maps together to produce a final ISC image corresponding to voxels that exhibited similar activation patterns across all participants.

A nonparametric bootstrapping method (https://brainiak.org/docs/brainiak.html) was used to test which voxels were significantly correlated with one another. For each iteration of bootstrapping, ISC values for all held out subjects were resampled with replacement and averaged across resampled subjects. The result produced a confidence interval around the true mean ISC value for each voxel. Ten thousand bootstrap iterations were performed and bootstrap hypothesis tests conducted to find all ISC values that were significantly greater than zero. Following bootstrapping, p-values were corrected using a whole brain FDR ($p < .05$), and resulting q-values (FDR corrected p-values) reinserted into brain images for subsequent analysis. This procedure was applied to all repetitions for both internal and external attention conditions in each movie.

We also performed targeted tests for hypothesized patterns. To do so, we selected four regions of interest (ROIs), two sensory processing regions and two associated with higher order processing. These ROIs were selected using the 17 network, 200 region parcellation scheme from Schaefer*, et al.* (36). For sensory regions, ROIs from early visual cortex and auditory cortex were selected (visual: RH_VisCent_ExStr_4, auditory: RH_SomMotB_Aud_1). For higher order regions, two parts of the DMN were selected (DMN; 37). To select the two DMN regions, we first conducted a meta-analysis of DMN regions using NeuroSynth (38), a platform that collects results across many fMRI studies. Searching 'Default Mode' yielded a statistical t-map corresponding to peak activations observed in 777 studies mentioning the DMN (*https://neurosynth.org/analyses/terms/default%20mode/*). We selected one parietal and one prefrontal region by first identifying the coordinates of peak activations from the meta-analysis and then finding regions that contained those peaks in the Schaefer atlas (right TPJ: RH_DefaultA_IPL_1, dmPFC: RH_DefaultA_PFCm_3). For the four selected ROIs, unthresholded ISC values were extracted from the ISC map averaged across held-out subjects. The voxels within each ROI were averaged to create one ISC value corresponding to the inter subject correlation for that particular ROI.

Results

Behavioral Results

The goal of the behavioral study was to systematically test the effect of stimulus salience and repetition on internal attention, external attention, and mind-wandering. Button presses throughout the experiment indicated moments when participants believed their attention had wandered from the task at hand. More button presses suggested greater difficulty in attending to the target task; less button presses suggested less difficulty. Figure 2A shows the mean results averaged across all subjects, for all trials involving the high-salience movies (Sherlock, Shrek, and The Office). The graph shows the number of button presses, across four repetitions of the movie, for the external attention task and the internal attention task. A 2 X 4 analysis of variance (ANOVA) showed a significant main effect of external versus internal attention and a significant interaction (for external versus internal attention, $F = 83.1$, $p < .001$; for the interaction, $F = 5.91$, $p < .001$). A main effect indicating an overall change in button presses across the four repetitions was absent, due to the opposing patterns in which button presses decreased across the four repetitions for the internal attention condition and increased across the four repetitions for the external condition ($F = 1.07$, $p > .05$). To understand the specific pattern of results within conditions, more targeted statistical tests are described next.

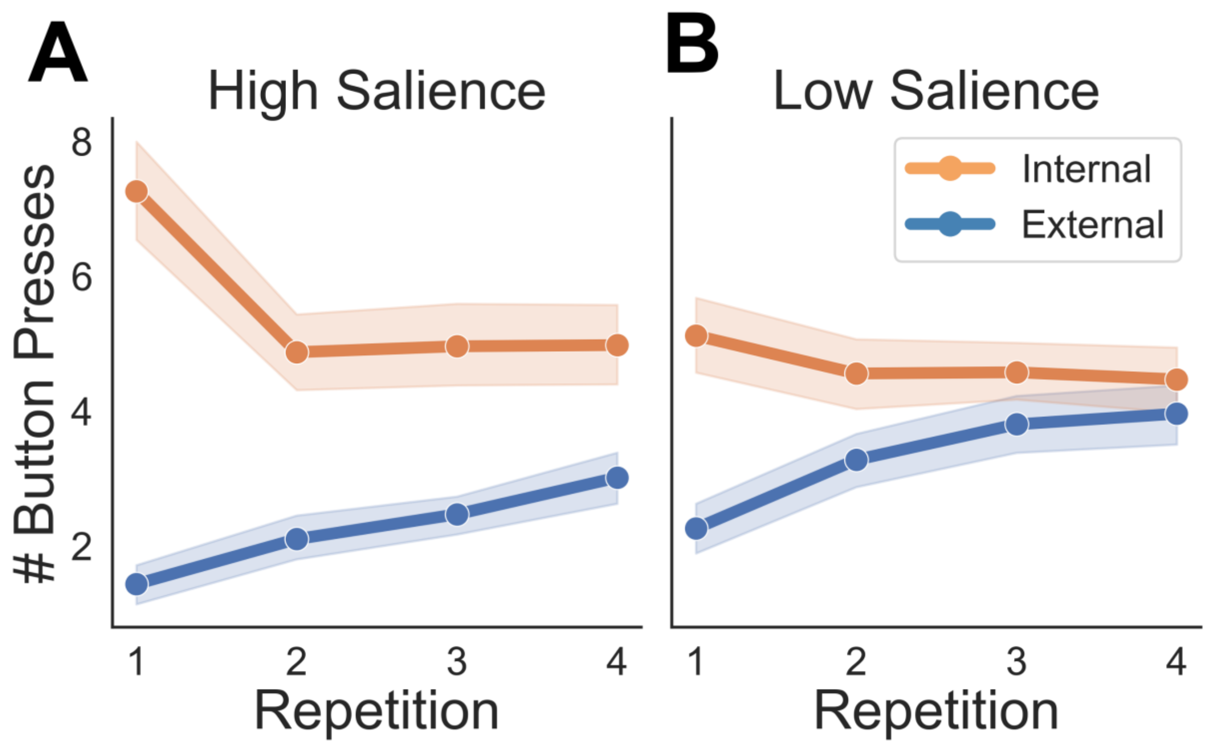

Figure 2. Number of self-reported mind-wandering events during attention task. **A.** Number of mind-wandering events for each repetition in internal (orange) and external (blue) attention

conditions for movies categorized as high salience. Standard error is shown in lighter shade. **B.** Number of mind-wandering events for movies categorized as low salience.

In Figure 2A, in the external attention task (blue line), when subjects were asked to attend to the movie for the first time, they performed with few mind-wandering events (mean of 1.44 button presses), suggesting that they had little trouble keeping their focus on the movie. In each successive repeat of the movie, more mind-wandering events occurred, until, on the final repetition, subjects pressed an average of 3.02 times. This increasing trend was statistically significant (regression analysis on external attention data, $t = 3.46$, $p < .001$). As the movie became more familiar, the subjects appeared to find it harder to keep their focus on it and engaged in more mind-wandering.

In contrast, the orange line shows the results for the internal attention task, when subjects were asked to attend to their own breath. On the first viewing of the movie, subjects had difficulty keeping their attention away from the movie and maintaining attention on their breath, registering an average of 7.26 mind-wandering events. By the fourth presentation of the movie, subjects found it easier to focus on their own breath, pressing the button an average of 4.98 times. However, the change in attention was not gradual over the four repetitions. Instead, the shape of the curve suggests that on the first viewing, there was an initial draw to attend to the engaging movie, distracting subjects from their task and producing more mind-wandering events, whereas on subsequent repetitions of the same video, subjects were able to resist the distraction to a similar extent. Button presses during the first exposure to the movie were significantly greater than presses during the second, third, and fourth repetitions, but button presses were not significantly different among the second, third, and fourth repetition (t test between first and second repetition, $t = 2.49$, $df = 112$, $p < .05$; t test between first and third repetition, $t = 2.35$, $df = 112$, $p < .05$; t test between first and fourth repetition, $t = 2.34$, $df = 112$, $p < .05$).

The data in Figure 2A also suggest that the internal attention task was overall harder than the external attention task. Across all four repetitions of the movie, the number of button presses, and thus mind-wandering events, was higher in the internal task than in the external task. Even on the fourth presentation of the movie, when one might think the movie had become so boring that subjects would find it difficult to keep their attention on it (and therefore the external attention task should be harder), and easy to keep their attention on their own breath (and therefore the internal attention task should be easier), nonetheless, the internal condition still had significantly more button presses than the external condition ($t = 2.97$, $df = 112$, $p < .01$). This finding does not mean that internal attention is always harder than external attention. Instead, it suggests that in the context of this task, when subjects watched high salience movies, external attention on the movie was easier than internal attention on their own breath.

Figure 2B shows the mean results for the low salience movies (instructional videos on origami, baking a cake, and brushing teeth). In some respects, the pattern is similar to that from the high salience movies, including a significant main effect in which button presses were overall greater for the internal versus the external attention condition (2 X 4 ANOVA, $F = 17.53$, $p < .001$), suggesting that the internal condition was overall more difficult than the external condition; a significant interaction between repetition and attention condition ($F = 2.64$, $p < .05$); and no significant main effect of repetition ($F = 0.59$, $p > .05$). In the external attention condition (blue line), button presses were low on first presentation of the movie and increased with subsequent repetitions, with a significant increasing trend (regression analysis on external attention data, $t = 3.04$, $df = 226$, $p < .01$). In the internal condition (orange line), though button presses were higher on first presentation and lower on subsequent repetitions, the trend was not significant ($t = -0.87$, $df = 226$, $p > .05$). Subjects seemed relatively uniformly able to resist the distraction of the movie through all repetitions; we did not observe a difference in button presses between the first and subsequent repetitions (t test between first and second repetition, $t = 0.75$, $df = 112$, $p > .05$; t test between first and third repetition, $t = 0.76$, $df = 112$, $p > .05$; t test between first and fourth repetition, $t = 0.90$, $df = 112$, $p > .05$).

Despite these similarities in the results of high and low salience movies, some differences were also observed. In the external condition, high salience movies were easier for subjects to attend. When subjects were asked to attend to the movie, they registered fewer mind-wandering events for the high salience movies than for the low salience movies (t test between high and low salience, in the external attention condition, $t =3.96$, $df =454$, $p <.001$). In the internal attention condition, the high salience movies were more distracting, making it harder for subjects to attend to their own breathing, as shown by the greater number of mind-wandering events for the high salience movies than for the low salience movies (t test between high and low salience, in the internal attention condition, $t =2.06$, $df =454$, $p <.05$).

Following the experiment, we asked participants to rate their level of engagement with each movie stimulus on a scale of 1 to 10. In total, we obtained 114 ratings for low salience movies (data available for 38 subjects X 3 movies) and 114 ratings for high salience movies. We found that self-reported levels of engagement were higher for the high salience videos (mean rating = 7.76) as compared the low salience videos (mean rating = 4.05). The difference was significant ($df = 226$, $t = 13.14$, $p < .001$). This result validates our separation of video stimuli into the high salience and low salience categories.

Neural Results: Whole Brain

ISC is commonly used to identify representations of external stimuli that are shared across subjects, often described as stimulus evoked synchrony. We used ISC as a neural signature of attention to the external stimulus that was shared across subjects (39). In the external attention condition, when participants were explicitly tasked with paying attention to the movie, we expected shared attention to persist across repetitions of the movie, corresponding to higher ISC. In the internal condition, we expected that ignoring the external stimulus would produce less shared representation of the external stimulus across all four runs, corresponding to lower ISC. Additionally, we expected that high salience movies would be easier to focus on in the external attention condition, and harder to ignore in the internal attention condition, as compared to the low salience stimuli, and that these differences would also be reflected in the ISC data.

To illustrate the ISC results, Figure 3 shows data for one example stimulus, the Sherlock movie. Each row shows the results of a single repetition of the movie, from the first presentation of the movie (repetition 1, top row) to the final presentation (repetition 4, bottom row). The first three columns show the results for the external attention condition, and the final three columns show the results for the internal attention condition. In the external attention condition, in the first repetition, the three views of the inflated cortex show the significant voxels in the ISC analysis. Significant voxels indicate that the movie stimulus was being processed in a consistent manner across subjects. In this condition, 56,636 voxels were significant. In the external attention condition, in the second repetition, the number of significant voxels was reduced (45,189 voxels). In the third repetition, even fewer voxels were significant (32,289 voxels) and in the fourth repetition, the smallest number were significant (28,082 voxels). This gradual reduction of voxels with each repetition mirrors the behavioral results (Figure 2A). With each repetition, subjects have greater difficulty attending to the movie, the movie affects the brain in a less consistent manner, and the inter-subject correlation therefore drops.

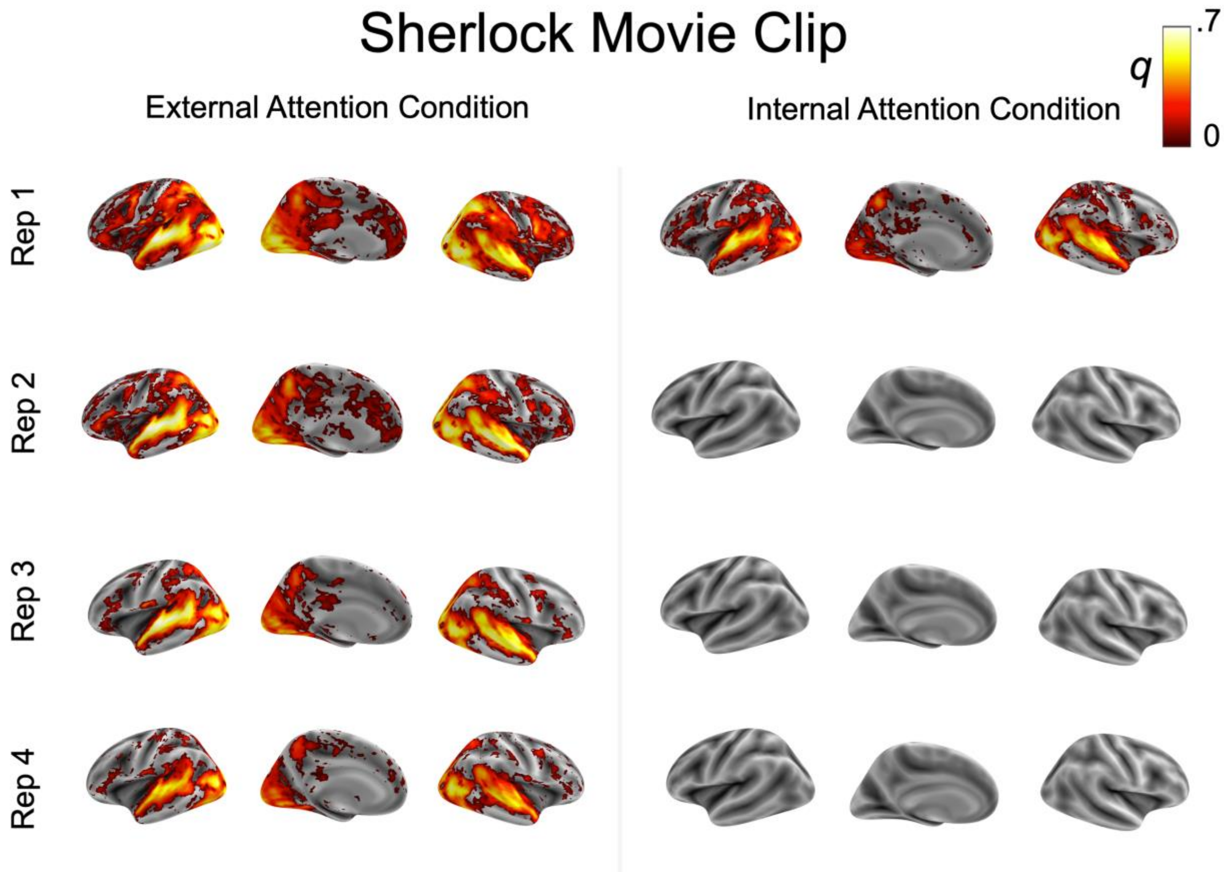

Figure 3. Whole brain inter-subject correlation across four repetitions in the external (left) and internal (right) attention conditions for the Sherlock movie. A nonparametric bootstrapping method was used to test which voxels were significantly correlated with one another. Following bootstrapping, p-values were corrected using a whole brain FDR ($p < .05$), and resulting q-values (FDR corrected p-values) plotted. Rows show movie repetitions 1 – 4.

In the internal attention condition, a different pattern was observed (see Figure 3, righthand side). Here, subjects attempted to focus attention on their breath and ignore the movie. In the first presentation of the movie (repetition 1), 33,373 voxels were significant, indicating that the subjects were not fully successful at blocking out the movie. Within at least some voxels, the movie was being processed in a consistent manner that correlated across subjects. In the subsequent repetitions, no significant voxels were obtained, indicating that the subjects were able to block out the movie sufficiently such that the ISC signal of stimulus processing was no longer detectable. Again, this pattern of findings mirrors the behavioral result (Figure 2B), in which the greatest change in attention to the movie occurred between the first and second presentation of the movie.

Figure 4A summarizes the mean results for all high salience movies. The blue bars show the result for the external attention condition, when subjects were required to attend to the movies. The four bars show the number of significant voxels in the ISC analysis across repetitions of the movie. Shown in this manner, the pattern is particularly clear. The first presentation of the movie corresponds to the greatest number of significant voxels, indicating the greatest amount of inter-subject correlation and therefore the greatest amount of cortical processing of the stimulus features of the movie. Each subsequent repetition is associated with a decreasing number of significant voxels, indicating a decreasing processing of the stimulus details, as the subjects' attention on the movie wanes and more mind-wandering events occur. In contrast, the red bars show the result for the internal attention condition, when subjects were required to ignore the movie and focus on their own breath. The first presentation of the movie shows the greatest number of voxels, indicating that despite the task, the movie did draw some attention and its stimulus details were processed. The second presentation of the movie shows fewer voxels, and subsequent presentations show no significant voxels, indicating that the subjects were able to block out the movie sufficiently such that the ISC signal of stimulus processing was no longer detectable.

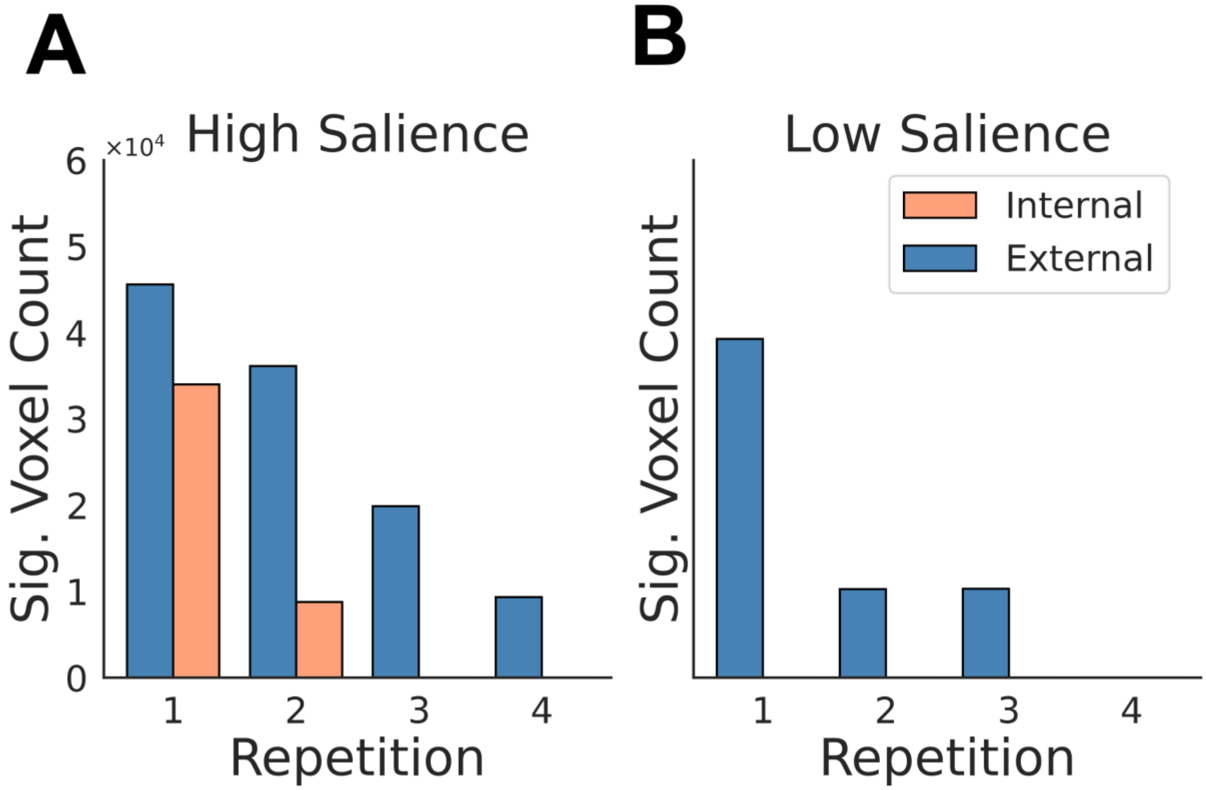

Figure 4. Number of voxels with significant inter-subject correlation for internal and external attention conditions. **A.** Results during viewing of high salience movies. **B.** Results during viewing of low salience movies

Figure 4B summarizes the results for the low salience movies. Once again, the blue bars show the result for the external attention condition. The first presentation of the movie corresponds to the greatest number of significant voxels, indicating the greatest amount of inter-subject correlation and therefore the greatest amount of cortical processing of the stimulus features of the movie. The second and third repetitions correspond to fewer significant voxels, and the fourth repetition yielded no significant voxels. Comparing the blue bars in the internal attention case (Figure 4B) to the external attention case (Figure 4A) shows a similar trend in which processing of the stimulus appears to decrease systematically as the movie is repeated. However, the number of significant voxels is overall lower and the decrease more rapid for the low salience videos, consistent with attention drifting from them more easily than from the high salience videos. In the internal attention condition, for the low salience movies, there were no significant voxels in any repetition of the movie. When subjects were asked to ignore the video and attend to their own breathing, even on the first presentation of the video, the subjects were able to block it out well enough that the ISC signal of stimulus processing was no longer detectable.

Neural Results: Regions of Interest

We hypothesized that shared representation of the external stimulus would be more robust in sensory areas across attention condition, while higher order areas would be more sensitive to idiosyncratic task processes, and therefore show less ISC. We analyzed two areas in sensory processing cortices, one in early visual cortex (EVC), and another in auditory cortex in the superior temporal gyrus (STG). We also analyzed two areas associated with higher-order cognition, the dorsal medial prefrontal cortex (DMPFC) and the right temporoparietal junction (RTPJ), both of which are hubs of the DMN. Figure 5 shows averaged ISC values for each attention condition, salience type, and region. In accord with the whole-brain results, here we found more synchrony for the external compared to the internal attention condition (blue lines versus orange lines) across all four brain regions. We also found more synchrony for the high salience compared to low salience condition (upper row versus lower row). When comparing sensory regions to higher order regions, the sensory regions generally exhibited more ISC than did the higher order regions. The STG showed the highest levels of synchrony, and the RTPJ the lowest. Across all regions, including sensory and higher order regions, ISC decreased with each repetition of the stimulus. These results suggest that representation of the movie may be more similar across subjects in sensory compared to higher order regions, but that sensory cortices are still susceptible to effects of repetition.

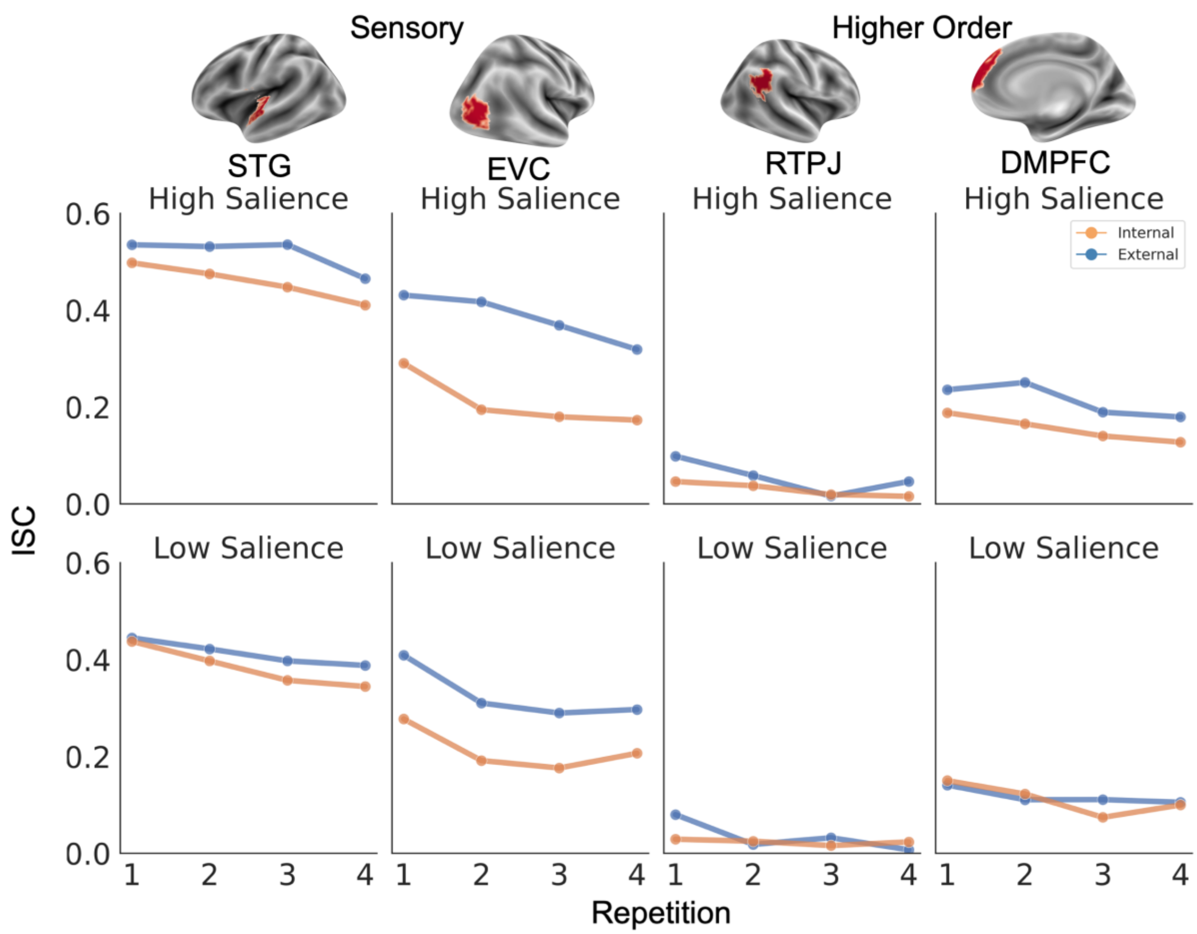

Figure 5. Inter-subject correlation values extracted for four cortical regions. Data from high salience movies shown in top row and from low salience movies shown in bottom row. Two regions on the left show example sensory areas; two regions on the right show examples of higher cognitive areas in the DMN.

Discussion

Our study asked whether human thought is naturally tuned towards a default internal state of cognition, called an internal bias of attention, or whether a similar automatic state can exist for external attention. We evoked both an external and internal attention state and compared the strength of each using self-reported mind-wandering events and whole-brain neural synchrony.

We found that across both external and internal attention conditions, the behavioral evidence of attention to the movies (based on reported mind-wandering events) and the neural evidence of attention on the movies (based on synchrony to the external stimulus) was highest on the first repetition relative to the last repetition, suggesting that the external stimulus was most easily represented and hardest to ignore when it was novel. We suggest that this attention on the novel, external stimulus represented a 'default' externally oriented state. In this interpretation, default, externally oriented states exist provided the right context. Our findings are in some ways comparable to the literature on external-internal multitasking paradigms in which information maintained in working memory conflicts with or facilitates an external task (40, 41).

We predicted that the strongest internal pull of attention would exist on the fourth repetition of the movie, producing a natural tendency to disengage from the external environment. This hypothesis was confirmed. According to the neural results, the external stimulus was least represented on the fourth repetition for both internal and external conditions, suggesting the least external attention. However, the results did include an interesting complexity. On the fourth repetition, there was still more mind-wandering when the task was to pay attention internally than when the task was to pay attention to the video. We had expected that four repetitions of attending to the same video would be more challenging than four repetitions of attending internally. Yet even after participants viewed the video four times, it was easier to pay attention to the movie than to ignore it. Despite previous literature advocating for a prepotent internally oriented bias of attention (1), this finding suggests a context in which an internal focus of attention is harder to maintain than an external one. The finding does not preclude that an internal bias exists in the broader context of day-to-day activities, but rather that there are some contexts, such as when engaged with movies (and perhaps also social media), that are exceptionally captivating, more so than internal simulation.

It is also worth noting that mind-wandering events when paying attention externally are not necessarily always the result of spontaneous internal thought, and mind-wandering events when paying attention internally are not necessarily always the result of external distractions. When the task is to pay attention externally, it is possible that off-task mind-wandering events are also due to other external distractors, in addition the internal cognition (e.g. memories). When the task is to pay attention internally, it is possible that mind-wandering events are due to spontaneous internal cognition in addition to the external sources. We did not have participants distinguish between mind-wandering sources as others have done (42, 43).

Mind-wandering

The term 'mind-wandering' has recently been criticized for its ambiguity, with some calling attention to the diverse range of definitions that vary by experimenter and task design (44, 45). Most commonly, mind-wandering has been defined as a shift in the contents of thought away from an ongoing task in the external environment to internally self-generated thoughts and feelings (17). However, others have suggested that the definition of mind-wandering must involve a reference to intentionality (46), as it can be influenced by volitional processes such as motivation (47) and can be intentional if the external task is not cognitively demanding (48).

The present study integrates both ideas, incorporating dominant external and internal attention states and their relationship to voluntary and involuntary cognition. Our findings are consistent with the view that mind-wandering can occur bidirectionally, from the internal to the external environment as well as from the external to the internal environment (49). Our findings also help to illustrate the link between mind-wandering, which involves spontaneous thought, and focused attention meditation, which involves controlled internal thought (50). Our task specifically supports a definition of mind-wandering that is involuntary and off task, regardless of the internal-external distinction.

Previous work manipulated the propensity toward involuntarily mind-wandering by scaling task difficulty, finding that less intentional mind-wandering events occur as the demands of the task increase and more intentional mind-wandering events occur as the task demands decrease (51). In the present study, instead of experimentally modifying task difficulty, we used repetition of an external stimulus to alter its salience. Repetition is known to evoke anticipatory responses in learning paradigms (52-54) and weaker responses (i.e. stimulus suppression) when no explicit objective is specified (55, 56). We show that repetition effects exist in the absence of a learning objective for naturalistic, multi-modal stimuli. Furthermore, the present results build upon previous notions of salience which typically used low level features of stimuli such as the contrast of neighboring pixels (57) or overall informational value (58) to quantify stimulus salience. Our results demonstrate that the abstract structure of the movie stimulus (the type of story) can influence the ease with which participants process external information.

Meta-awareness and control

The relationship between meta-awareness and mind-wandering is primarily explored in mindfulness and meditation. Findings include that meta-awareness affords increased control (59, 60), decreased mind-wandering events (61-64), and increased ability to deflect negative internal thought (65, 66). However, these studies tend to test meta-awareness towards internal or external contents, without comparing the two. Studies that directly compare them focus on unimodal meditation objects that do not dynamically change (43, 67). The present study provides further evidence that meta awareness and control can alter automatic internal and external modes of cognition in a dynamically changing environment (21).

Default Mode Network

The DMN classically activates during internally oriented thought and deactivates when engaged with external tasks. However, this traditional view has been challenged by results showing its involvement in communication (68), social cognition (69, 70), and temporal event segmentation (71, 72). Our experiment tests one aspect of DMN function: its role in internal compared to external attention. If the DMN is purely an internal network, it should encode no shared external attention across subjects. However, according to the present data, it did.

We selected two regions in the DMN for focused analysis. We found that the RTPJ and DMPFC showed less sensitivity to the attention manipulation (external versus internal) as compared to the lower level sensory regions which showed greater sensitivity to the attention manipulation. One potential reason might be that the DMN regions are involved in attention functions unique to meta awareness and control, and that those functions are similar whether the task requires external attention or internal attention. Such an interpretation coheres with previous accounts of higher order regions in which the DMPFC is involved in second order representations of task performance (73, 74) and the RTPJ is critical for representing attention states (75, 76). However, it is also worth noting that the DMPFC showed some sensitivity to the external content, while the RTPJ did not. Thus, certain components of the DMN may be involved in dynamically integrating external and internal information, showing a sensitivity to both external and internal processing, while other DMN regions may be more sensitive to internal attention processes alone. The present results tentatively point to a role for at least some components of the DMN in both external and internal modes of processing.

Data Availability

All anonymized data are publicly available online (https://github.com/isaacrc/metaawareness-and-default-states)

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